LIGO-G030464-00-Z

Analysis for burst gravitational waves with TAMA300 data

- Burst gravitational-wave search using TAMA300 data
    - Based on an excess power filter
    - Non-Gaussian noise reduction
    - Event candidate list

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S. Miyoki, N. Mio, S. Moriwaki, K. Numata, N. Kanda, Y. Aso,
M.-K. Fujimoto, K. Tsubono, K. Kuroda,
and the TAMA collaboration

Introduction (1)

- Burst gravitational wave detection -

- Short bursts of gravitational waves (from stellar core-collapse etc.)
  - Waveforms : poorly predicted
    ⇨ cannot use matched filtering method for detection

⇩

- Look for unusual events in the detector output
  - Several filters have been proposed (Pulse correlation, Slope, TF Cluster, Excess power, ...)
    - Detection efficiencies have been discussed with Gaussian, stationary noises

    - Some assumptions on waveform → higher efficiency
    - Few assumptions → low efficiency

Introduction (2)

- Non-Gaussian noises -

- **Main output signal of a detector**

$$= \underbrace{(\text{Stationary, Gaussian noise})}_{\text{Stable operation}} + \underbrace{(\text{Burst GW signals}) + (\text{Non-Gaussian noise})}_{\text{Non-Gaussian events}}$$

Burst filters:

Look for and sensitive to

Unpredicted, non-stationary waveforms

- **Burst GW signals, Non-Gaussian noise**

⇩

Detection efficiency is limited by non-Gaussian noises

⇩

Non-Gaussian noise rejection is indispensable

- **Detector improvement**
- **Data analysis with a single detector**
- **Coincidence analysis**

Introduction (3)

- TAMA Burst gravitational wave analysis -

- In our analysis ...
  - Excess power filter
    - Look for excess power in the detector output
    - Less assumptions: Time scale and Frequency band

  - Non-Gaussian noise rejection
    - Reduce false alarm rate (better efficiency)
    - Time scale selection

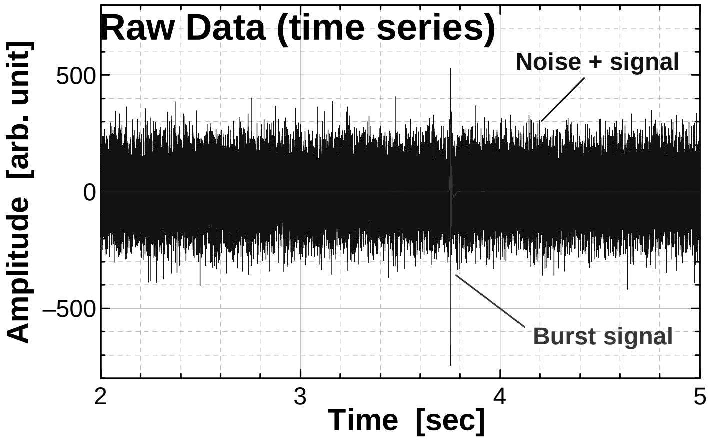
  - TAMA data
    - Data taking 6
      - 1000 hour observation run in 2001

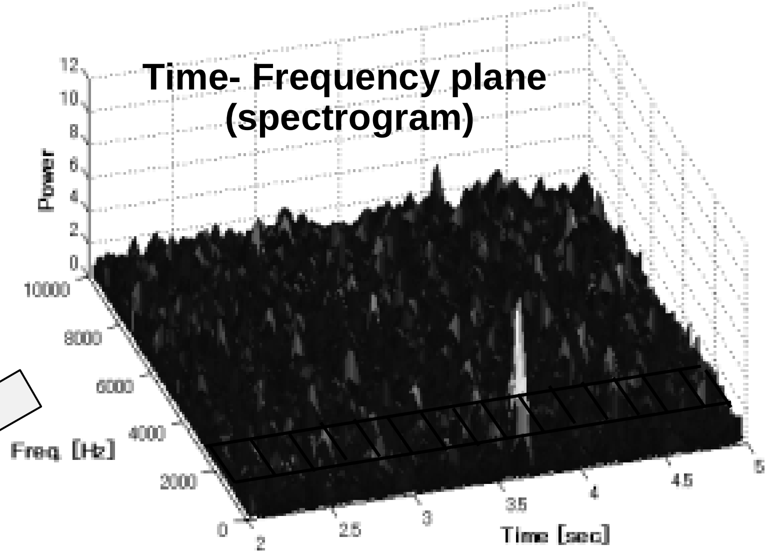
  - Event candidate list

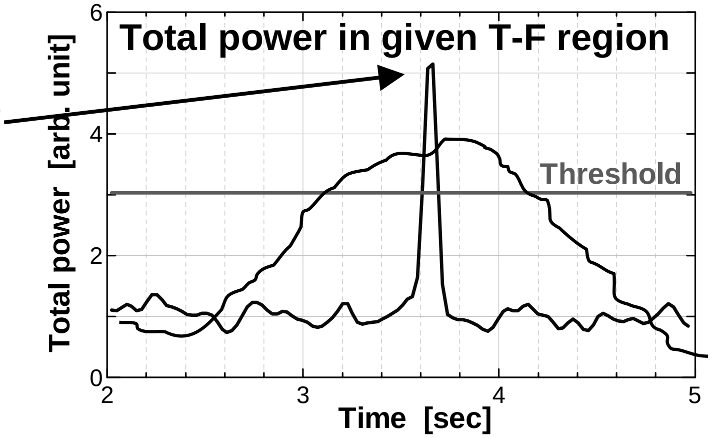
Burst filters (1)

- Excess power filter -

- **Excess power filter**
  - **Total power in selected time-frequency region**







Signal !!!

Effective if time-frequency range of the signal is known

Non-Gaussian noise evaluation (1)

- Reduction of non-Gaussian noise -

- **Non-Gaussian noise reduction**

  Distinguish GW signal from non-Gaussian noises with time-scale of the 'unusual signals'

⇨ **GW from gravitational core collapse < 100 msec,**
Noise caused by IFO instability > a few sec

- **2 statistics in detector output**
  - **Averaged noise power**
  - **2^{nd}-order moment of noise power**

⇩

Estimate parameter : 'GW likelihood'

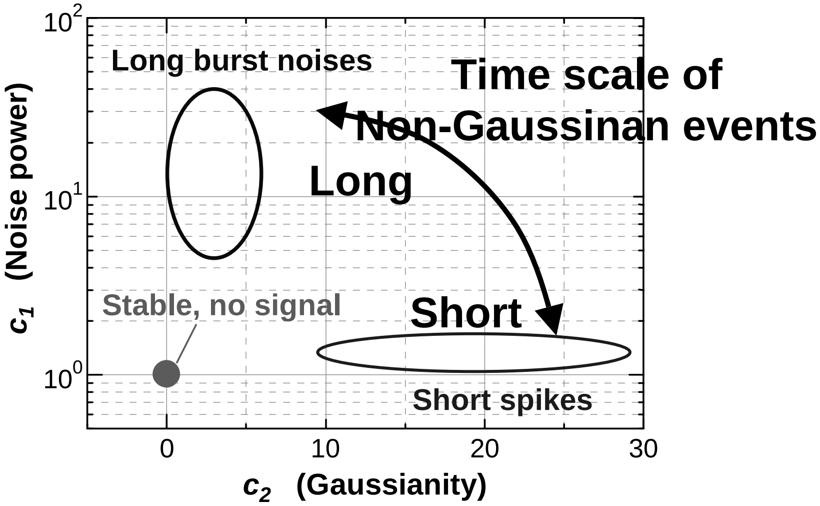
$$C_1 = \langle P_j \rangle$$

$$C_2 = \frac{1}{2}\left(\frac{\langle P_j^2 \rangle}{\langle P_j \rangle^2} - 2 \right)$$

Non-Gaussian noise evaluation (2)

- noise evaluation with C_1-C_2 correlation -

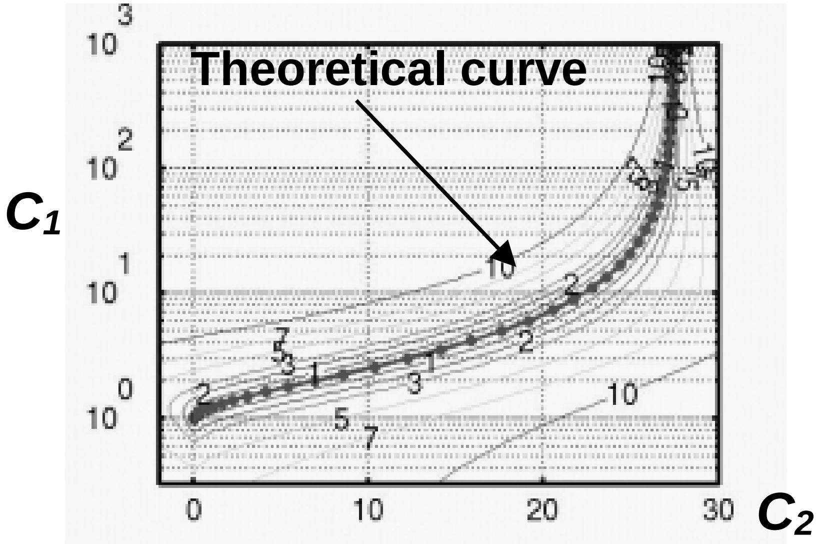
- **Correlation plot: C_1 and C_2**
  - **Different behaviors for**
    - **Stable operation**
    - **Short pulse**
    - **Degradation of noise level many burst noises**



- **Distance (D) to the curve**

  → 'Likelihood' to be GW signal

Reduce non-Gaussian noise
Without rejecting GW signals



TAMA300 data (1)

-Data taking runs with TAMA300 -

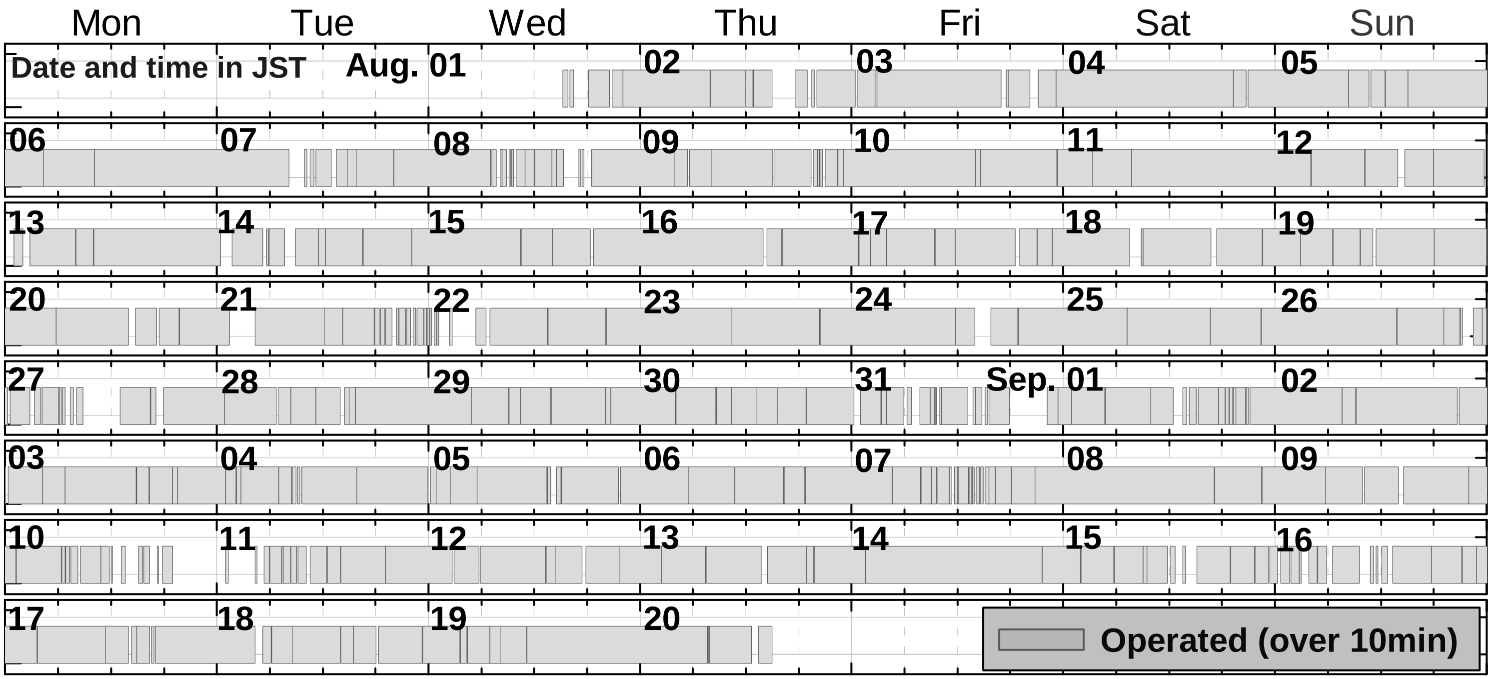
Data Taking		Objective	Observation time	Typical strain noise level	Total data (Longest lock)
DT1	August, 1999	Calibration test	1 night	3x10^{-19} /Hz $^{1/2}$	10 hours (7.7 hours)
DT2	September, 1999	First Observation run	3 nights	3x10^{-20} /Hz $^{1/2}$	31 hours
DT3	April, 2000	Observation with improved sensitivity	3 nights	1x10^{-20} /Hz $^{1/2}$	13 hours
DT4	Aug.-Sept., 2000	100 hours' observation data	2 weeks (night-time operation)	1x10^{-20} /Hz $^{1/2}$ (typical)	167 hours (12.8 hours)
DT5	March, 2001	100 hours' observation with high duty cycle	1 week (whole-day operation)	1.7x10^{-20} /Hz $^{1/2}$ (LF improvement)	111 hours
DT6	Aug.-Sept., 2001	1000 hours' observation	50 days	5x10^{-21} /Hz $^{1/2}$	1038 hours (22.0 hours)
DT7	Aug.-Sept., 2002	Full operation with Power recycling	2 days		25 hours
DT8	Feb.-April., 2003	1000 hours Coincidence	2 months	3x10^{-21} /Hz $^{1/2}$	1157 hours (20.5 hours)

TAMA300 data (2)

- Data Taking 6 -

- **Data Taking 6 (August 1- September 20, 2001, 50 days)**

➡ **Over 1000 hours' observation data**



TAMA300 data analysis (1)

- Selection of parameters -

- **Selection of time window, frequency band**
  - **Time window: smaller → larger S/N**
    - Lower frequency resolution
      (Easily affected by AC line etc.)
  - **Frequency band: wider → larger S/N**
    - Use frequency band
      with larger noise level

$$\Delta t = 200\ [\mathrm{msec}],$$
$$\Delta f = 500\ [\mathrm{Hz}]$$

- **Determination of thresholds**
  - **Threshold:**
    - **Distance to theoretical curve: D_{th}**
      Should be optimized
      depending on noise behavior
    - **False dismissal rate: estimated by**
      Monte-Carlo simulation
      Theoretical calculation

$$D_{th} = 5,$$
$$(\mathrm{F.D.} < 1\mathrm{ppm})$$

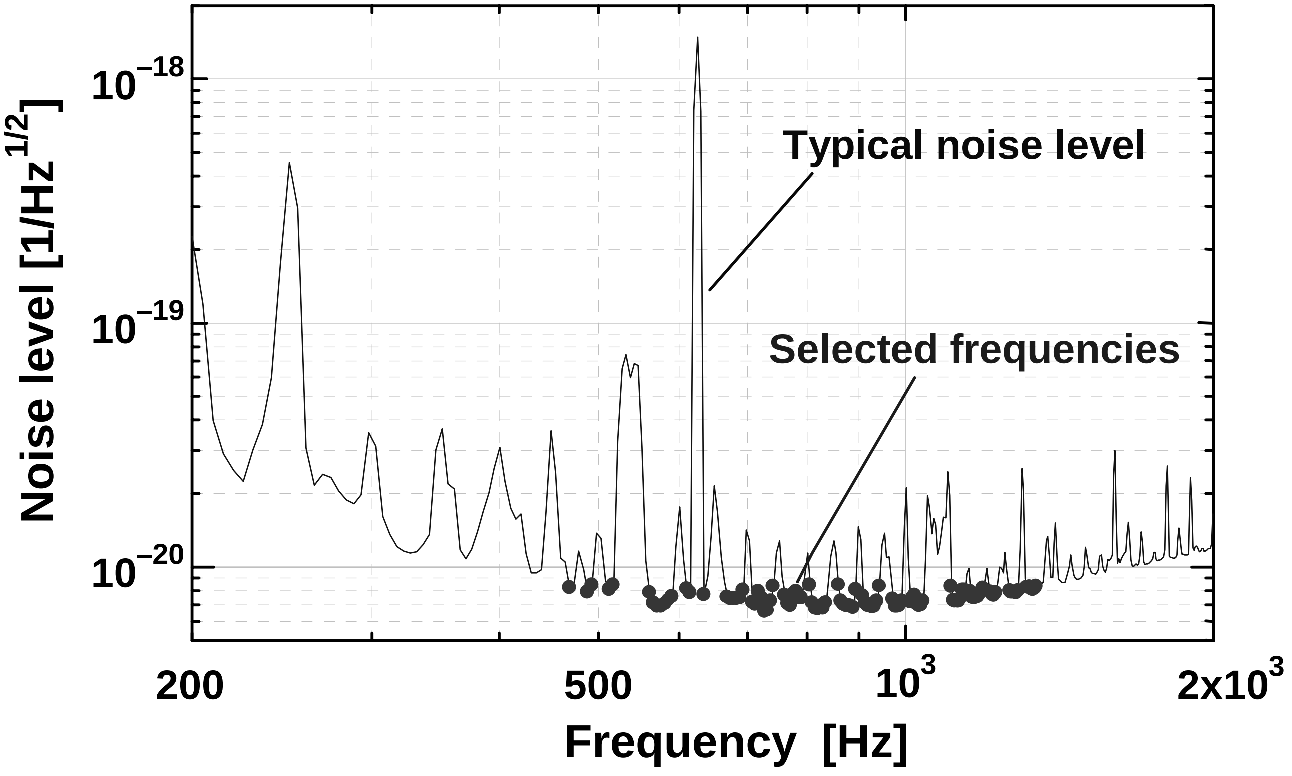
TAMA300 data analysis (2)

- Typical noise level of TAMA300 -

- **Typical noise level of TAMA300 during DT6**

  About 7×10^{-21} /$\mathrm{Hz}^{1/2}$

  - **Selection of frequency bands for analysis → *Δf=500* [Hz]**



Masaki Ando, 5th Edoardo Amaldi Conference (July 09, 2003, Pisa, Italy)

TAMA300 data analysis (3)

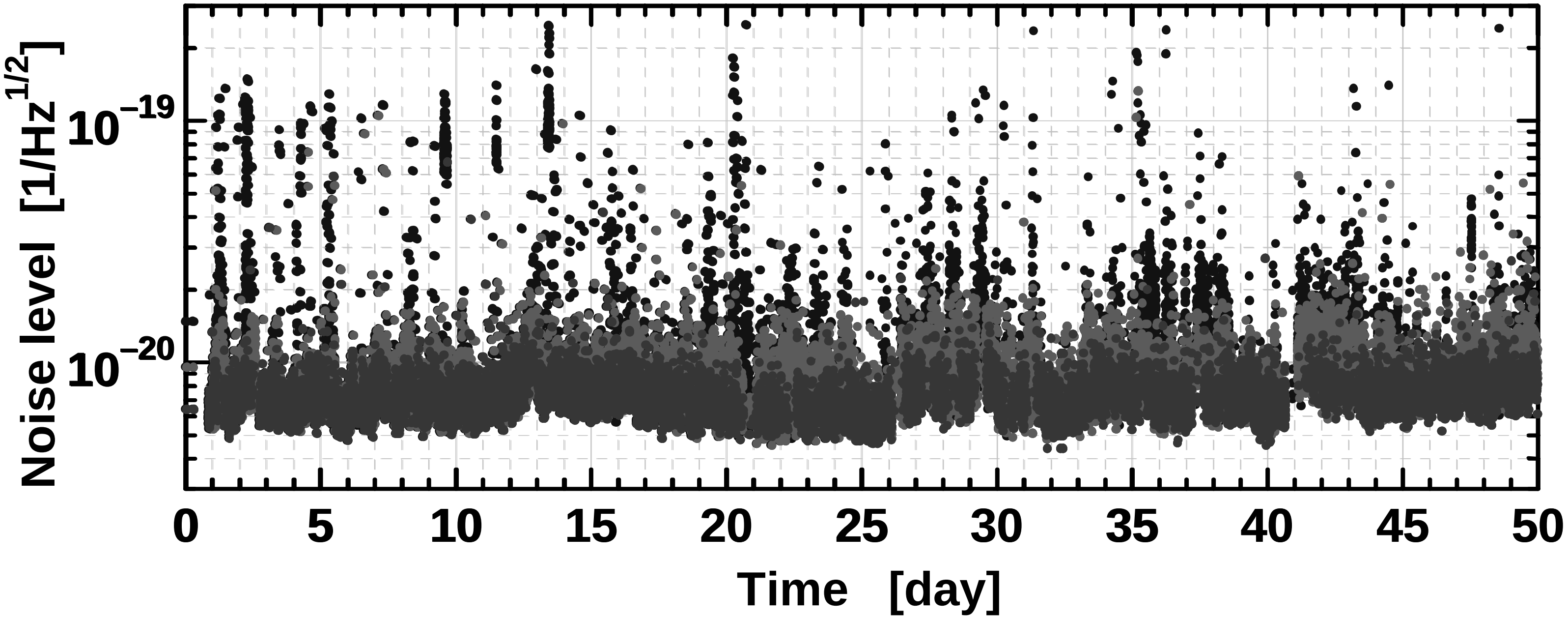
- time-series data -

- **Data Taking 6 time-series data**

Confirm reduction of non-Gaussian noises (in daytime)

Rejected data : 60%   (False dismissal rate < 1ppm)

(23% if threshold is D_{th}=20)



TAMA300 data analysis (4)

- event rate -

- **Event rate (Integrated histogram)**
  - **Non-Gaussian noise rejection**

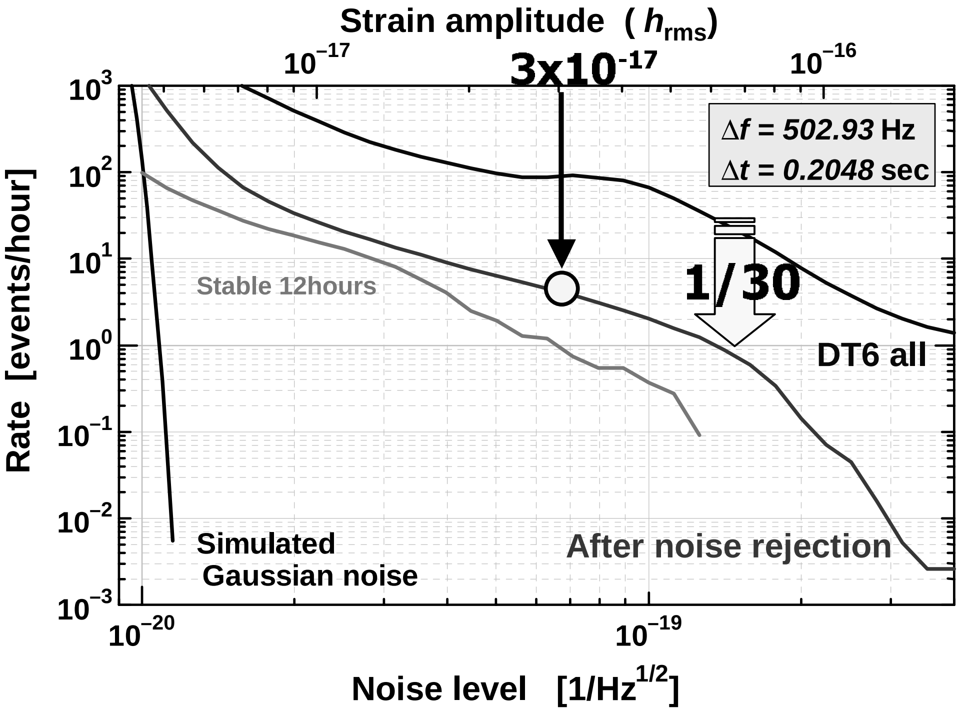
    ⇨ 1/30 improvement

    (380 hour data survived)
  - **h_{rms}: $3x10^{-17}$ (1msec spike)**

    → 4 events/hour
  - **Still far from Gaussian**
  - **Stable 12 hours**

    h_{rms}: $3x10^{-17}$

    → 1 events/hour



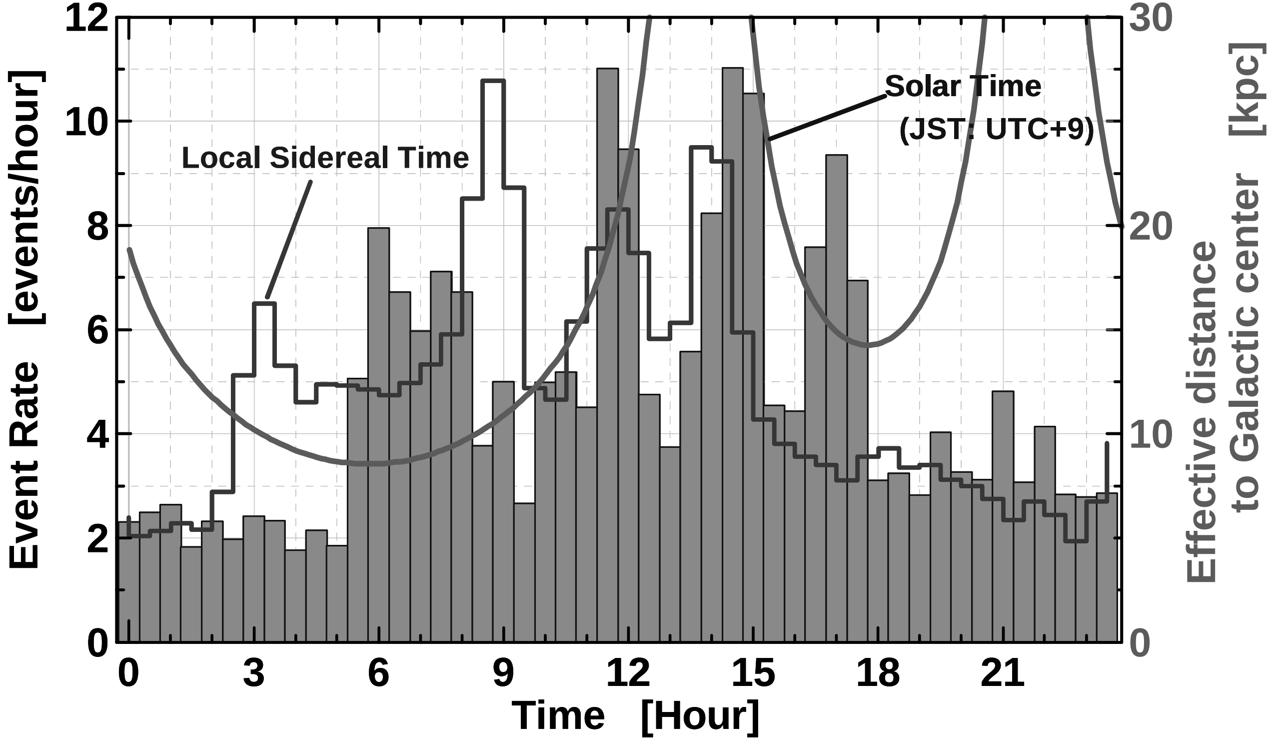
TAMA300 data analysis (5)

- Event rate change in a day -

- **Event rate dependence on time**

  for events : $h_{rms}>3\times10^{-17}$ (6.6×10^{-20} $1/Hz^{1/2}$)

  - **Total : 4 events/hour**
  - **Factor of 5 difference between daytime and midnight**
  - **Sidereal time analysis ➡ no clear correlation**



Summary

- **Burst gravitational wave search**
  - **Data: TAMA300 DT6, 1000-hour data (Summer 2001)**
  - **Target: Short bursts < 100msec**
  - **Method: Excess power filter**
    Non-Gaussian noise rejection: Time scale selection

    - **Reduce non-Gaussian noises**

    - **Better upper limits, detection efficiency**

↓

- **Event candidate list**
  - **Burst GW signal event rate**
    4 events/hour for $h_{rms} \sim 3\mathrm{x}10^{-17}$ (1msec pulse)
    (or $6.6\mathrm{x}10^{-20}$ $1/\mathrm{Hz}^{1/2}$, $3\mathrm{x}10^{-21}$ 1/Hz)
  - **Reduce non-Gaussian noise: 1/30 - 1/300**

Current and Future Tasks

- **Burst filter**
  - **Optimization of parameters**
    (Data length, Frequency band, Thresholds)
  - **Other filters**
    Better efficiency to GW events

- **Non-Gaussian noise rejection**
  - **Single detector**
    - **Detector improvement**
    - **Data processing (veto using auxiliary signals)**
  - **Correlation with other detectors**
    - **Other GW detectors**
      → with LIGO, ROG (in preparation)
    - **Other astronomical channels**
      (Super novae, Gamma-ray burst, etc.)

- **More data : we have 2000-hour data up to DT8**

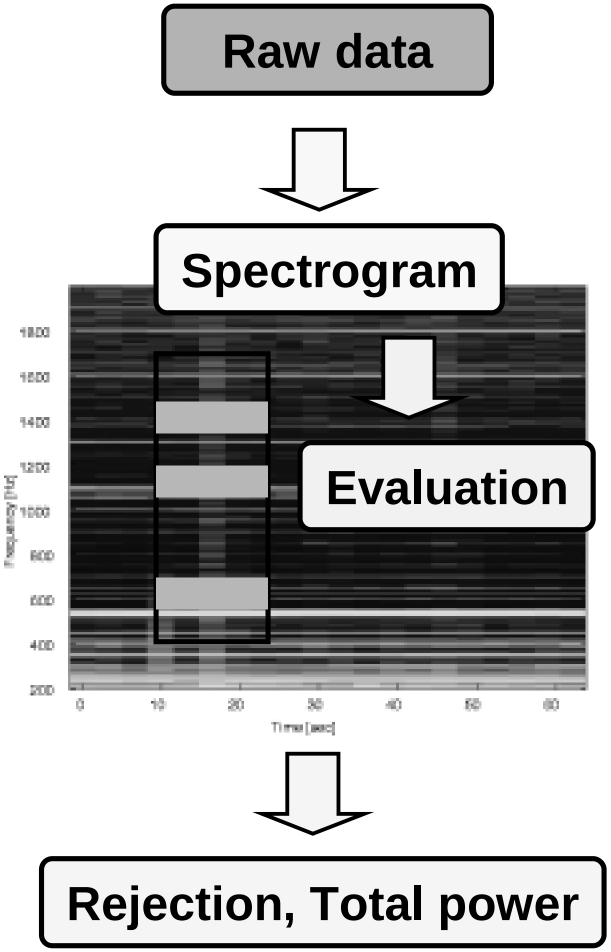
Contents

Burst filter implementation

- Data processing -

- **Data Processing**
  1. **Calculate Spectrogram by FFT**
  2. **Sum up the power in frequency components to be evaluated**
  3. **Evaluate GW likelihood (Threshold D_{th})**
  4. **Reject given time region if it has large 'non-GW likelihood'**

- **'Filter' outputs for each time chunk**
  - **Total power in selected time-frequency region**
  - **'Stable time' or detector 'Dead time'**



Raw data

Spectrogram

Evaluation

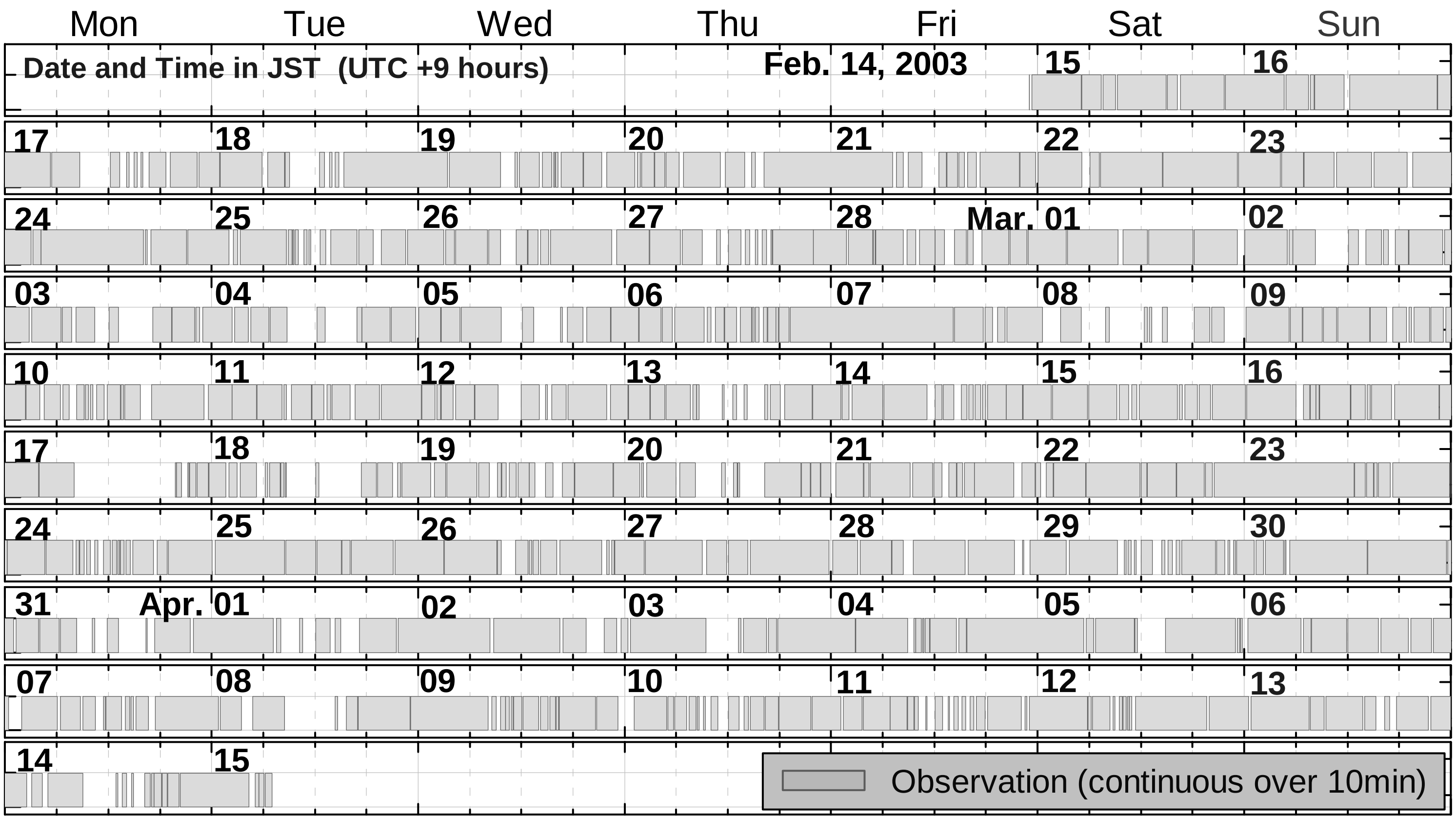
Rejection, Total power

Data taking 8 (1)

- Detector operation status in DT8 -

- Operation status calendar

  Total operation : 1157 hours



Detection efficiency (1)

- GW waveforms -

- **Numerical simulation of super novae**

  H.Dimmelmeier et al,

  Astron. Astrophys. 393 (2002) 523.

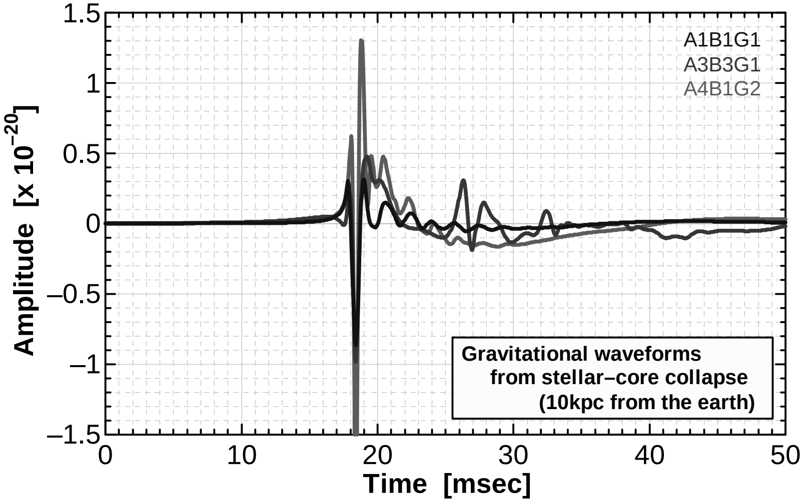
  ⇨ **26 gravitational waveforms**

  - **Relativistic rotational core collapse**
  - **Various waveforms**
  - **Discrete three parameters**

    Degree of diff. rotation
    Initial rotation rate
    Adiabatic index

  ⬇

  Not suitable for templates

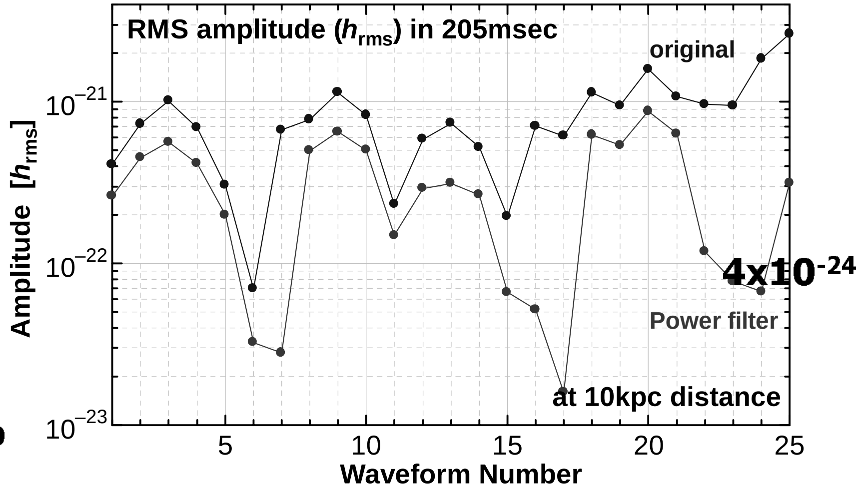


- **Common characteristics**

  ⇨ **Short bursts**

- **Power filter analysis**
  - **500Hz bandwidth**

    (between 400-1300Hz)
  - **averaged power in 200msec**
  - **Average of amplitude ratio : 42%**



Detection efficiency (2)

- Galactic model -

- **Galactic model**

  Assumed model for neutron star distribution

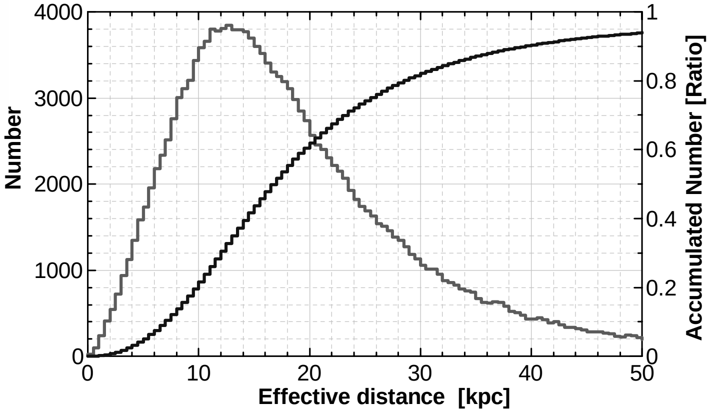
$$dN = e^{-R^2/2R_0^2} e^{-Z/h_z} RdRdZ$$

(R_0: 4.8 kpc, h_z: 1 kpc)

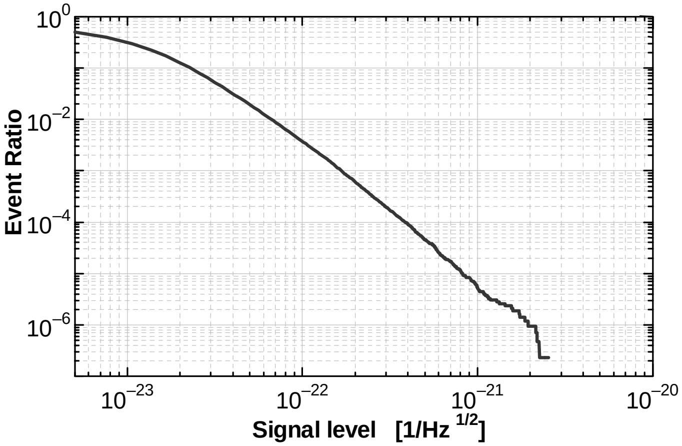
  - **Consider source direction**

    ⇨ **Effective distance**

⬇



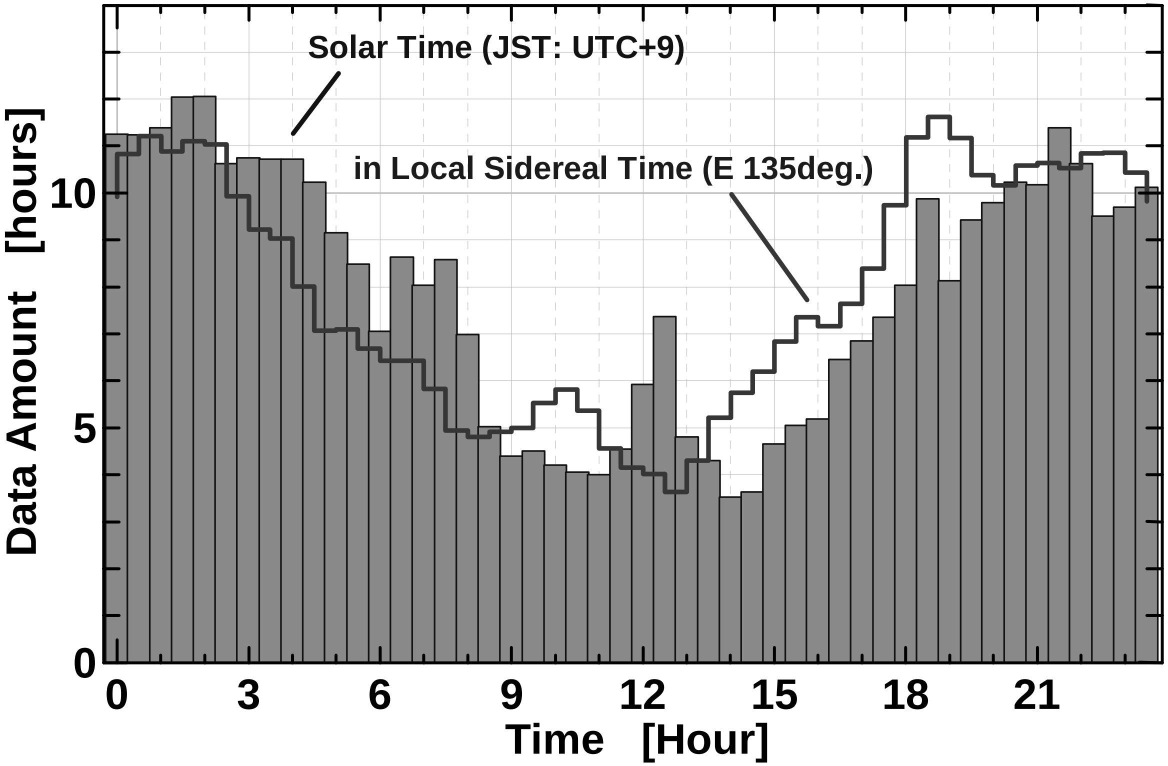
- **Power filter analysis**
  - **Ratio of larger events than a given signal level**



TAMA300 data analysis

- Stable data dependence on time -

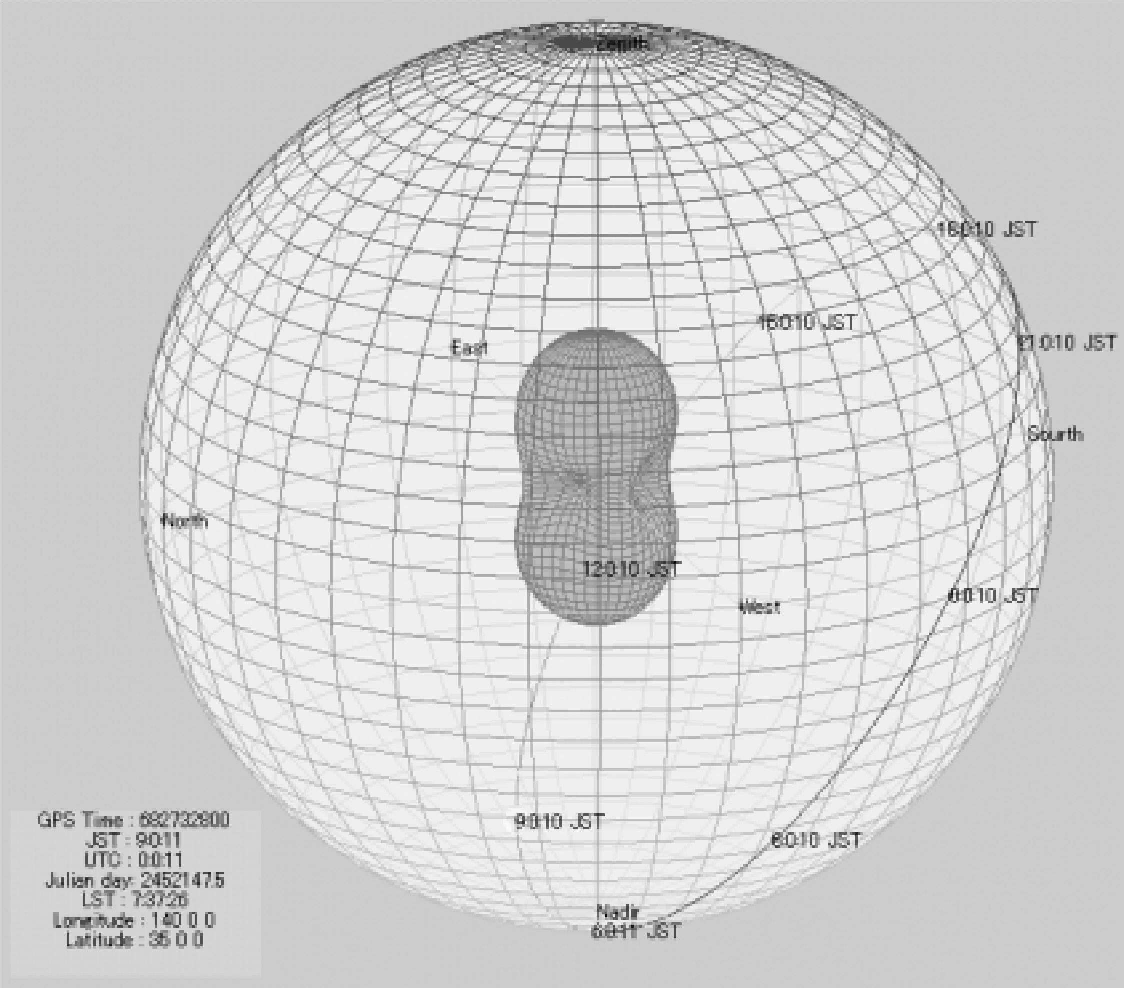
- **Stable observation time**
  - **Total stable obs. time : 380hours**
    - **Factor of 3 difference between daytime and midnight**
    - **Peak at the lunch time**



TAMA300 data analysis

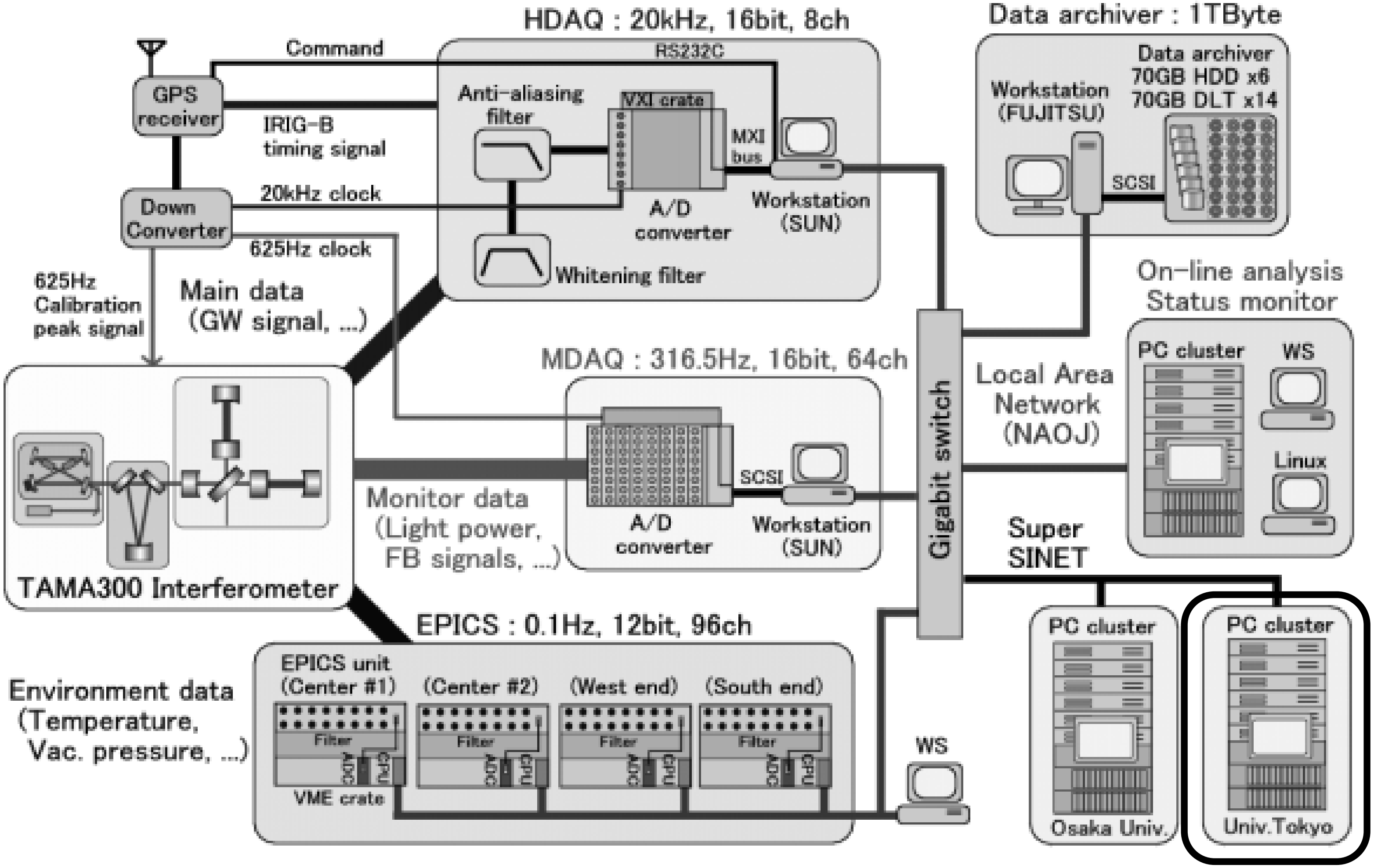
- Detector sensitivity to Galactic center -

- **Daily motion of the Galactic center**



TAMA data analysis

- Data distribution and analysis -



Non-Gaussian noise rejection

- Hardware and software -

- **Computer for analysis**
  - **Beowolf PC cluster**
    - Athlon MP2000+ 20CPU, 10 node
    - Storage : 1TByte RAID
      60GByte local HDDs/each node
    - Memory : 2GByte
    - Connection : Gigabit ethanet
  - **Software**
    - OS : Red Hat Linux 7.2
    - Job management : OpenPBS
      (Portable Batch-queuing System)
    - for parallel processing : MPI
    - Compiler : PGI C/C++ Workstation
    - Software : Matlab, Matlab compiler

Non-Gaussian noise rejection

- Computation time -

- **Analysis time: 90% is for spectrogram calculation**
- **1 file (about 1 min. data)**

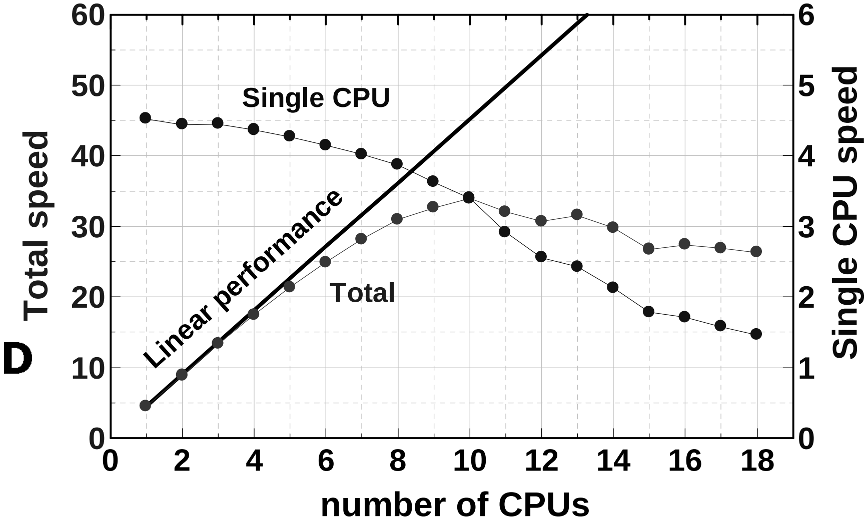
  2560 FFT calculations ($N_{\mathrm{FFT}} = 2^{12}$)
  - Distributed calculation with several CPUs **(not a parallel computation)**
    - **Assign data files to each CPU**
    - **Minimum load for network**
    - **Easy programming, optimization**

  - **Benchmark test**

$$\frac{(\mathit{Data\,Taking\,Time})}{(\mathit{Time\ for\ Analysis})} = \begin{cases} 4.5 & (1\mathrm{CPU}) \\ 35 & (\mathrm{max}) \end{cases}$$

    - Degradation with many CPUs
      - **Data-readout time from HDD**
      - **Limited memory bus in each node**

Data analysis speed **(data time/calc. time)**



Burst wave analysis
- proposed filters -

- **Excess power**
  - **Excess power statistic for detection of burst sources of gravitational radiation**
    Warren G. Anderson, Patrick R. Brady, Jolien D. E. Creighton, and Éanna É. Flanagan
    (University of Texas, University of Wisconsin-Milwaukee etc),
    Phys. Rev. D 63, 042003 (2001)
- **Slope detector**
  - **Efficient filter for detecting gravitational wave bursts in interferometric detectors**
    Thierry Pradier, Nicolas Arnaud, Marie-Anne Bizouard, Fabien Cavalier,
    Michel Davier, and Patrice Hello (LAL, Orsay),
    Phys. Rev. D 63, 042002 (2001)
- **Clusters of high-power pixels in the time-frequency plane**
  - **Robust test for detecting nonstationarity in data from gravitational wave detectors**
    Soumya D. Mohanty (Pennsylvania State University),
    Phys. Rev. D 61, 122002 (2000)
- **Correlation with single pulse**
  - **Detection of gravitational wave bursts by interferometric detectors**
    Nicolas Arnaud, Fabien Cavalier, Michel Davier, and Patrice Hello (LAL, Orsay),
    Phys. Rev. D 59, 082002 (1999)

Non-Gaussian noise evaluation (2)

- noise evaluation with C_1-C_2 correlation -

- **Detector output model**

  Stationary-Gaussian noise + GW signal, non-Gaussian noise

- **Correlation plot:**

  C_1 and C_2

  - **Stable operation**

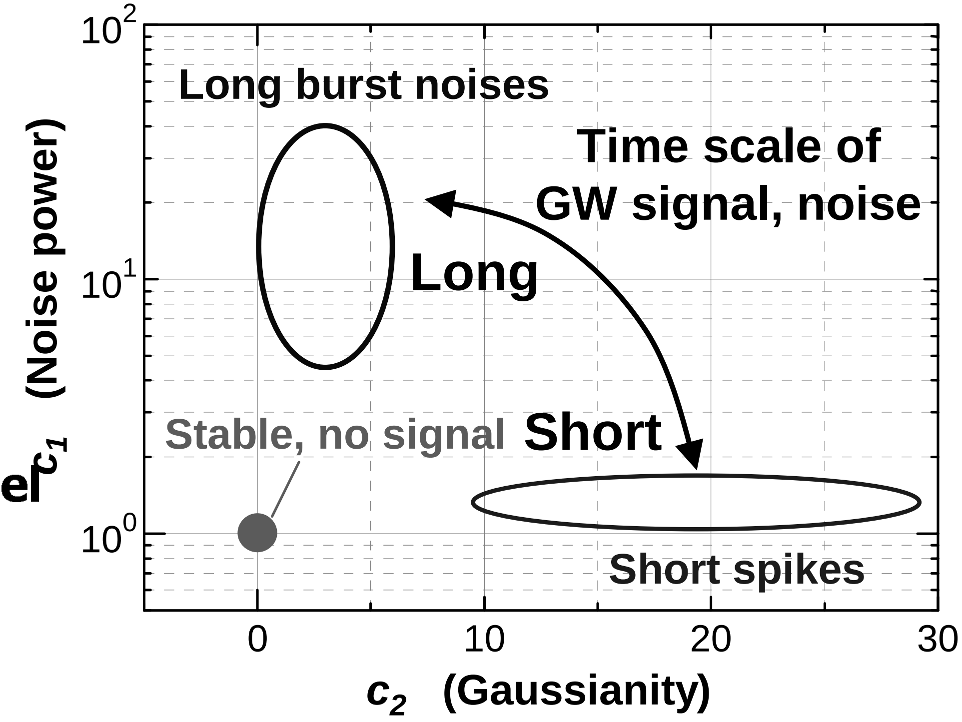
    $$C_1 \to 1, \quad C_2 \to 0$$

  - **Short pulse**

    $$C_1 \to \text{small}, \quad C_2 \to \text{large}$$

  - **Degradation of noise level many burst noises**

    $$C_1 \to \text{large}, \quad C_2 \to \text{small}$$



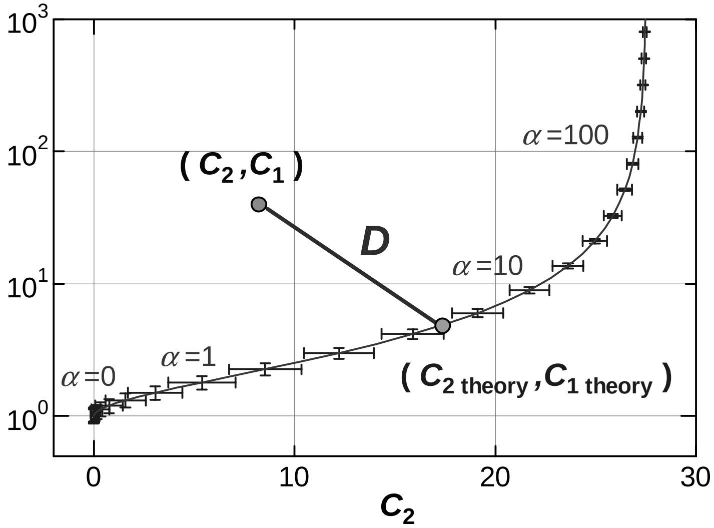
Non-Gaussian noise evaluation (4)

- Distance from theoretical curve -

- **Theoretical calculation**
  - Detector output
    → Gaussian noise + Non-Gaussian noise

C_1, C_2, variance (S_1, S_2), covariance (S_{12})
function of signal amplitude (α)

C_1, C_2 with certain amplitude (α)
→ 2-D Gaussian distribution



- **Distance from the curve (deviation)**

$$D^2 = \frac{1}{M}\left\{S_2\left(C_1 - C_{1\mathrm{theory}}\right)^2 - 2S_{12}\left(C_1 - C_{1\mathrm{theory}}\right)\left(C_2 - C_{2\mathrm{theory}}\right) + S_1\left(C_2 - C_{2\mathrm{theory}}\right)^2\right\}$$

$$\left(M = S_1 S_2 - S_{12}^2\right)$$

- **Search α for minimum D**

Non-Gaussian noise evaluation (3)

- theoretical curve in correlation plot -

- **Data model**

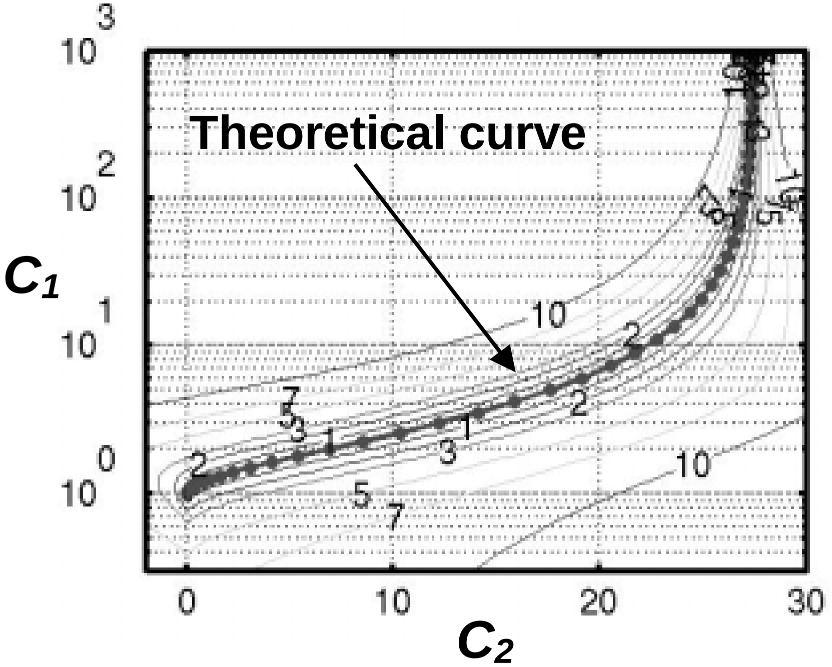
  Gaussian noise + GW signals

  Theoretical curve in correlation plot
  (Consistent with simulation results)

- **Distance (*D*) to the curve**

  --- Likelihood to be GW signal

  Reduce non-Gaussian noise
  Without rejecting GW signals



TAMA300 data evaluation (4)

- Estimation of averaged noise level -

- Estimation of averaged (typical) noise level
    - Critical for non-Gaussian noise rejection

    - Calculated for each frequency band
        - Use latest stable data

          Noise level < typical x$\sqrt{2}$

          Gaussianity < 0.1
        - Average for 6 min.